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Production of η_c, χ_c and χ_b Mesons in Proton–(Anti)Proton Collisions

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Abstract A multitude of precise measurements of J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ (n = 1, 2, 3) production cross sections and polarizations have been conducted in recent years. These make the investigation of feed-down decays from heavier states crucial to fully comprehend their production mechanisms. Also the study of new, so far unmeasured quarkonium states is essential to complete our picture of quarkonium production. This paper discusses the experimental results of prompt η_c, χ_c and χ_b production cross sections, ratios and feed-down fractions in proton–proton (pp) and proton–antiproton ($p\bar{p}$) collisions. Comparing these measurements to calculations in the NRQCD framework shows a dominance of the color-singlet contribution in case of the χ_c and χ_b production, while the η_c cross section is already well described by only the color-singlet contribution.

1 Introduction

Despite its many successes, the strong force as described by QCD does not give us an understanding of bound state formation. Quarkonia, bound $c\bar{c}$ and $b\bar{b}$ quark states, constitute an ideal experimental probe to study hadronization. First, they consist of two quarks and thus are the simplest manifestation of the strong binding force. Second, the quarks involved are heavy. Therefore, the creation of the initial quark–antiquark pair and the bound state formation happen at very different time scales.

Until the mid-90s, the initial quark–antiquark pair was believed to be produced in a color-singlet state. But the measurement of the J/ψ and $\psi(2S)$ cross sections at CDF [1] in $p\bar{p}$ collisions at a center-of-mass energy $\sqrt{s} = 1.8$ TeV showed that the theoretical expectations based on the leading order (LO) calculations of the color-singlet Model (CSM) were about 50 times too small. This lead to the development of the non-relativistic QCD (NRQCD) factorization approach where quarkonia can also be produced as colored pairs. The successive non-perturbative evolution of the initially colored pair to a bound color-singlet quarkonium state is described by long distance matrix elements (LDMEs) that are treated as free parameters. The NRQCD framework succeeded in describing the cross section measurements at the Tevatron, but also predicted quarkonium polarizations that were later proven to be in strong disagreement with the measurements at the Tevatron [2].

With the advent of the LHC, new and more precise measurements of J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ cross sections and polarizations became available [3–37], triggering also new developments in theory. NRQCD calculations were updated to include the recent data [38–45], but also new avenues were explored, such as fragmentation contributions (see [46,47] and references within) or extensions to NRQCD [48]. One study applied a data-driven approach and put more emphasis on the polarization data as it directly relates to the production process [49].

More precise and consistent data of J/ψ and $\Upsilon(nS)$ mesons increases the importance of understanding the role of the feed-down decays from heavier χ states. To complete our picture of quarkonium production, it

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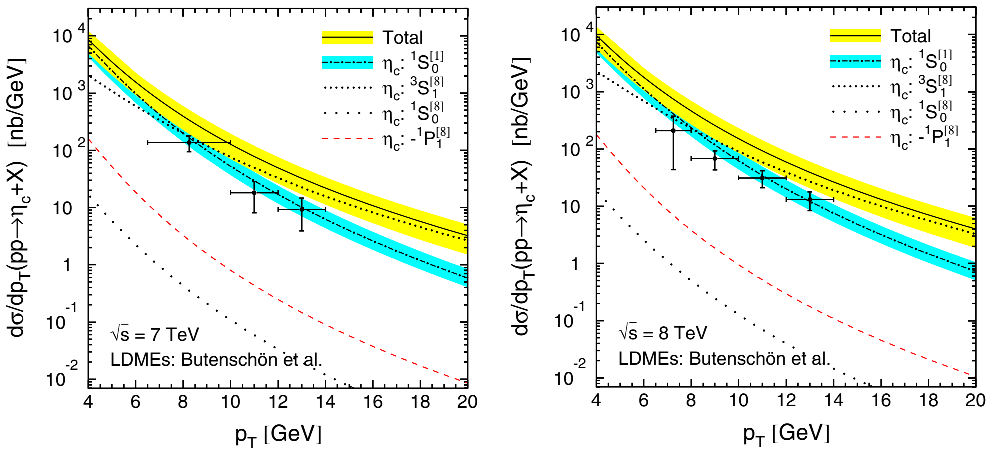

Fig. 1 Differential cross section $d\sigma/dp_T$ of prompt η_c mesons as function of p_T at $\sqrt{s} = 7$ (*left*) and 8 TeV (*right*): the measurement by LHCb [50] is compared to the total prediction of the NLO NRQCD calculations [53] using LDMEs calculated in Ref. [40] as well as the color-singlet ($^1S_0^{[1]}$) and the different color-octet contributions ($^3S_1^{[8]}, ^1S_0^{[8]}, ^1P_1^{[8]}$). Taken from Ref. [53]

is also crucial to measure the production of quarkonium states that have not been studied before and that now became available at the LHC energies, such as the η_c meson.

In this paper, measurements on the production of η_c, χ_c and χ_b mesons are discussed. In case of the charmonium family, the focus is placed on the prompt production which is experimentally easily subtracted from the non-prompt component coming from B-hadron decays using the information on the particle's lifetime.

2 Production of Prompt η_c Mesons

LHC has provided pp collisions at unprecedented center-of-mass energies up to $\sqrt{s} = 13$ TeV and unmatched quarkonium production rates. This allowed the LHCb collaboration to make the first measurement of the prompt η_c cross section using the $p\bar{p}$ decay channel. The systematics were partially canceled by determining prompt yields of η_c relative to those of $J/\psi \to p\bar{p}$. The resulting absolute cross section as function of transverse momentum, p_T, is shown in Fig. 1 for $\sqrt{s} = 7$ and 8 TeV. It was calculated using the J/ψ cross sections from Refs. [51,52], integrated over the kinematic region of the measurement: $p_T > 6.5$ GeV and rapidity, $2 < y < 4.5$.

LHCb is the best experiment to measure charged hadron final states due to its unparalleled charged-hadron identification. In contrast, identifying different types of charged hadrons is harder for general purpose experiments, such as ATLAS and CMS, which makes the study of $\eta_c \to p\bar{p}$ difficult.

The LHCb measurement made it possible to test one of the pillars of NRQCD, the heavy quark spin symmetry (HQSS). HQSS relates the LDMEs of the spin-triplet state, J/ψ, to the ones of the spin-singlet state, η_c. The authors of Ref. [53] carried out the full next-to-leading order (NLO) calculations in the NRQCD factorization framework, using HQSS and including the color-singlet and all relevant color-octet components. As shown in Fig. 1, the resulting predictions overshoot the experimental cross sections of prompt η_c mesons. The $^1S_0^{[1]}$ singlet contribution alone agrees very well with the results of LHCb, pointing to a disagreement with HQSS, according to which the $^3S_1^{[8]}$ term, with its LDME equal to the $^1S_0^{[8]}$ LDME of J/ψ production, should be large.

However, the exact validity of such spin-counting relations has been shown to be questionable, on the basis of data-driven arguments [49]. Moreover, the observed dominance of the $^1S_0^{[1]}$ term for η_c production is not in contradiction with the global picture of quarkonium production: LHC data are perfectly consistent with production mechanisms dominated by unpolarized $^1S_0$ (octet) pre-resonance states [49], possibly indicating the existence of an alternative LDME hierarchy, at the same time simpler and stronger than the one currently foreseen in the framework of NRQCD.

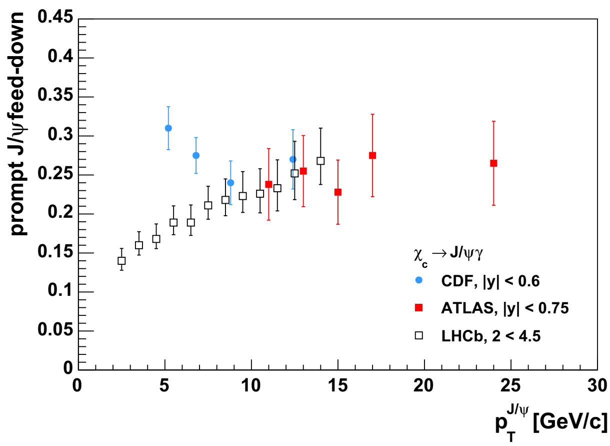

Fig. 2 Fraction of J/ψ mesons coming from χ_c decays as function of $p_T^{J/\psi}$, measured by CDF [54], ATLAS [55] and LHCb [56]

3 Production of Prompt χ_c Mesons

Only a few measurements of P-wave quarkonium production are currently available. Such measurements are essential for understanding the feed-down contribution of the P-wave quarkonia to the lower lying S-wave states. Experimentally, the feed-down decays are not distinguished from the directly produced mesons.

The χ_c states are identified using their radiative decays to the J/ψ. The photons are mostly detected via their conversion to e^+e^- pairs, allowing for a separation of the χ_{c1} and χ_{c2} peaks, due to the increased energy resolution of converted photons compared to photons detected only in the electromagnetic calorimeter (ECAL).

Figure 2 shows the fraction of χ_c mesons decaying to J/ψ as function of J/ψ transverse momentum, $p_T^{J/\psi}$, as measured by CDF [54], ATLAS [55] and LHCb [56]. No distinction between the different spin states was made. The results of LHCb and ATLAS align very well and are consistent with the values of CDF at higher $p_T^{J/\psi}$. The typical feed-down fractions are around 15–20% at $p_T^{J/\psi} < 10$ GeV raising to ca. 30% for $p_T^{J/\psi} > 15$ GeV. The understanding of this substantial and experimentally not distinguishable contribution of χ_c states to the J/ψ production is crucial for comprehending J/ψ production.

Measuring the production rate of χ_{c2} relative to χ_{c1} is experimentally preferable over determining absolute cross sections as large parts of the systematic uncertainties cancel. The ATLAS collaboration is so far the only experiment that has measured the absolute χ_{c1} and χ_{c2} prompt cross sections as well as their ratio [55]. Figure 3 shows the relative prompt production rate of χ_{c2} to χ_{c1} mesons, determined by ATLAS, compared to the results of CDF [57], CMS [58] and LHCb [59,60], assuming unpolarized production. Two measurements of LHCb are depicted: One is obtained with conversion photons only, as was done in the CDF, ATLAS and CMS experiments, while the second one used photons detected in the ECAL. The latter method has an inferior energy and mass resolution which requires a more elaborate mass fit to disentangle the different χ_c peaks. The $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio is essentially flat at around 0.75 for $p_T^{J/\psi} > 5$ GeV for measurements using conversions, while the values of the LHCb measurement using ECAL photons cluster around unity for $5 < p_T^{J/\psi} < 8$ GeV.

The experimentally measured values are about half of the expected ratio of 5/3. This value 5/3 is derived from calculations in the NRQCD framework, relying on HQSS, where the ${}^3S_1^{[8]}$ color-octet LDME is predicted to dominate χ_c production at high p_T [61]. When fitting the available experimental data on the χ_{c2}/χ_{c1} ratio to extract the LDMEs, the authors of Ref. [61] discovered that the color-singlet component dominates the χ_c production, as shown in Fig. 3. Moreover, they found that the ratio is highly sensitive to the relative contributions of the color-octet LDMEs.

4 Production of χ_b Mesons

Compared to the charmonium system, the bottomonium family shows an increased complexity in the structure of states and feed-down decays. For a long time, the $\Upsilon(3S)$ has been believed to be almost free of any feed-down, similar to the $\psi(2S)$ state. However, in 2011, the ATLAS collaboration [62] found an excess at the

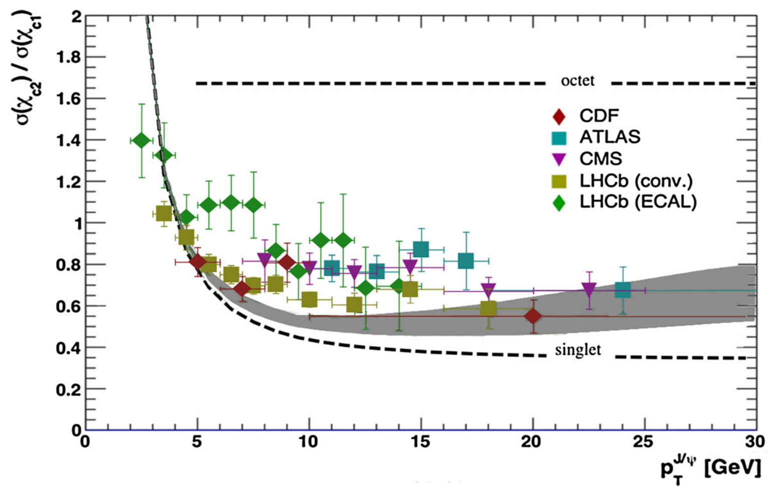

Fig. 3 Prompt production cross section ratio of χ_{c2} over χ_{c1} mesons as function of $p_T^{J/\psi}$, assuming unpolarized χ_c production: The measurements of CDF [57], ATLAS [55], CMS [58] and LHCb, using conversions [59] and ECAL photons [60], are compared to color-singlet, color-octet and total NRQCD predictions [61]. Adapted from Ref. [61]

mass of 10.53 ± 0.005 (stat.) $\pm$ 0.009 (syst.) GeV, consistent with the $\chi_b(3P)$ state. This resonance has since been confirmed by LHCb [63] and D0 [64]. LHCb additionally measured the feed-down fraction of $\chi_b(3P)$ decaying to $\Upsilon(3S)$ to be in the range of 44–36% for $24 < p_T^{\Upsilon(3S)} < 40$ GeV, which is much larger than previously expected.

Also the fractions of $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons originating from $\chi_b(mP)$ decays with m = 1, 2, 3 were measured as

$$\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)} \equiv \frac{\sigma(pp \to \chi_{b1}(mP)X)}{\sigma(pp \to \Upsilon(nS)X)} \times \mathcal{B}_1 + \frac{\sigma(pp \to \chi_{b2}(mP)X)}{\sigma(pp \to \Upsilon(nS)X)} \times \mathcal{B}_2, \tag{1}$$

where σ denotes the cross section and $\mathcal{B}$ refers to the branching fraction. The $\chi_b(mP)$ mesons are reconstructed via their decays to $\Upsilon(nS)$ and a photon which in turn converts to an e^+e^- pair.

Figure 4 shows the feed-down fractions as function of $p_T^{\Upsilon(nS)}$ determined by the LHCb experiment in pp collisions at $\sqrt{s} = 7$ and 8 TeV. The fractions of $\Upsilon(1S)$ mesons coming from $\chi_b(1P)$ and $\chi_b(2P)$ decays measured at CDF [67] in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ GeV are also depicted. The LHCb feed-down fraction $\chi_b(1P) \to \Upsilon(1S)\gamma$ of around 30% for $p_T^{\Upsilon(1S)} > 22$ GeV agrees with the values measured by CDF, while the LHCb fraction of $\chi_b(2P)$ decaying to $\Upsilon(1S)$ mesons is consistently lower than the one determined at CDF. In particular at low p_T, CDF found a much lower fraction of directly produced $\Upsilon(1S)$ mesons (50.9 ± 8.2 (stat.) $\pm$ 9.0 (syst.)%) than the more precise LHCb measurement indicates.

The relative production rate of $\chi_{b2}(1P)$ to $\chi_{b1}(1P)$ mesons as function of $p_T^{\Upsilon(1S)}$ have been determined by LHCb [63] and CMS [65]. The two measurements, assuming unpolarized production, are shown in Fig. 5. The ratios are consistent with each other, as well as with being flat around 0.85. This experimental finding is again in disagreement with the value of 5/3 expected from NRQCD calculations. The results in Fig. 5 are also compared to NRQCD predictions obtained from the ratio of χ_c mesons and scaled according to their p_T and mass [61]. The predictions undershoot the data points.

5 Summary

The unprecedented center-of-mass energies and large quarkonium production rates at the LHC open the door to more precise and novel measurements of quarkonium production. This has triggered several new experimental results highly relevant for the understanding of hadronization. Several of these results challenge parts of NRQCD where quarkonia can be produced as colored pairs.

In particular, the new data enabled the LHCb collaboration to study the prompt η_c production cross section for the first time. The experimental results are in disagreement with the NLO NRQCD predictions, but are described very well by only the color-singlet component.

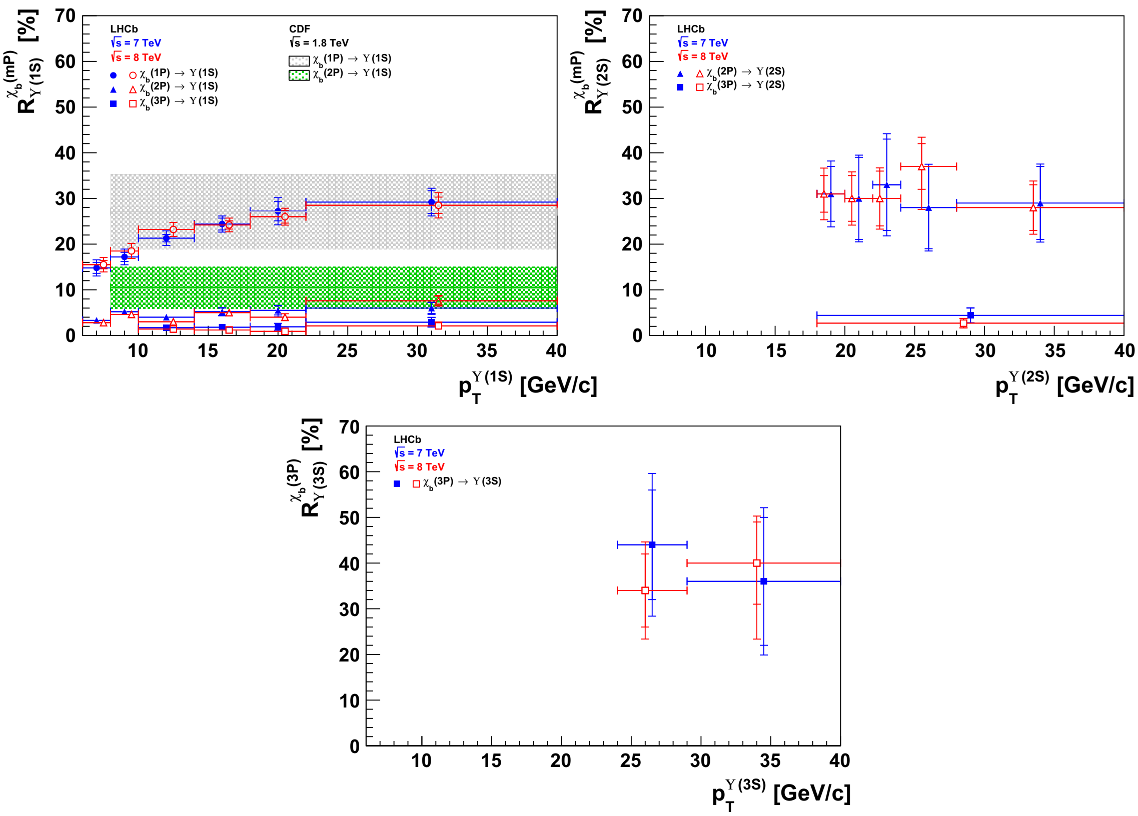

Fig. 4 Fractions of $\Upsilon(nS)$ mesons coming from $\chi_b(mP)$ decays as function of $p_T^{\Upsilon(nS)}$, measured by LHCb [66] and CDF [67]

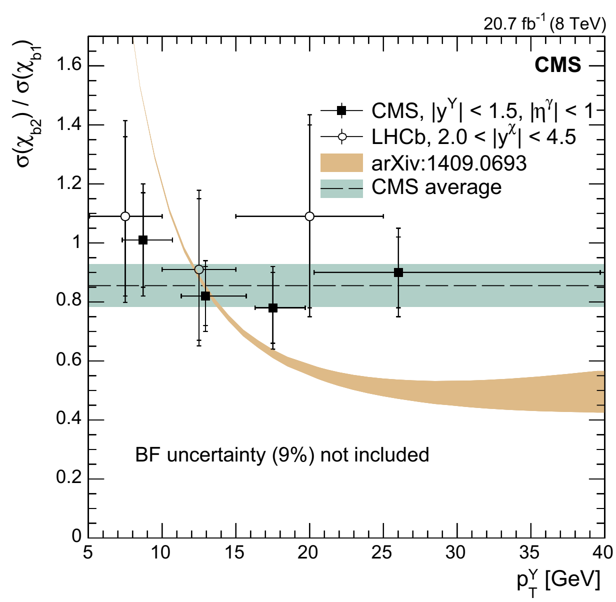

Fig. 5 Production cross section ratio of $\chi_{b2}(1P)$ over $\chi_{b1}(1P)$ mesons as function of $p_T^{\Upsilon(1S)}$: The measurements by CMS [65] and LHCb [63] are compared to NRQCD predictions [61]. Taken from Ref. [65]

Furthermore, the precise measurements of J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ cross sections and polarizations over the recent years increase the importance of studying χ states and their production, of which we still have little knowledge. The fraction of feed-down decays from P-wave states to the lower lying S-wave states is substantial with up to 30% and even up to 44% for J/ψ and $\Upsilon(nS)$ production, respectively. The production cross section ratio of χ_c was determined by the CDF, ATLAS, CMS and LHCb collaborations, while the one of $\chi_b(1P)$ mesons was only studied by CMS and LHCb so far. Both ratios were found to be consistent with being flat. The NRQCD prediction for the ratio is highly sensitive to the relative contributions of color-singlet and color-octet matrix elements. The average experimental values are clearly below the value of 5/3 corresponding to pure octet production, seemingly indicating that color-singlet components dominate.

In summary, measurements on prompt η_c, χ_c and χ_b production cross sections, ratios and feed-down fractions in proton–(anti)proton collisions at the LHC and the Tevatron have been presented. From the comparison of these results to theory, it is clear that substantial theoretical and experimental work remains to be done before a clear picture of quarkonium production emerges.

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